Building Research Establishment Digest

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DIGEST 150

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Concrete: Materials

Concrete has usually to meet one or more of four functional requirements; strength, durability, fire protection and thermal insulation, and its properties depend on the correct selection of materials as well as on good practice on site. There is a wide range of cements and aggregates from which to choose. This digest brings up to date the information about their main characteristics and the properties of concretes made from them, previously published in Digest 5 which is now withdrawn. It describes the effects on concrete strength and workability of adjusting mix proportions according to the grading zone of the fine aggregate and includes a new section about admixtures. Reinforcing materials are not discussed.

Cements

Most concrete is made with ordinary or rapid-hardening Portland cement but there are other cements that will produce concretes with more specialised properties. The following notes amplify the information given in Table 1.

Ordinary Portland cement: develops strength sufficiently rapidly for most concrete work; as with all the other cements discussed, the rate of hardening is accelerated by warmth and retarded by cold. Its resistance to attack by acids and sulphates is generally low.

Rapid-hardening Portland cement: does not set any faster than ordinary Portland cement but after setting it develops strength more rapidly. Formwork can therefore be struck earlier and the cement is useful in cold weather.

Sulphate-resisting Portland cement: has a modified chemical composition compared with ordinary Portland cement to provide resistance to attack by sulphate solutions which are found in some soil situations. It has moderate low-heat properties.

Extra-rapid-hardening cement: is a Portland cement containing approximately 2 per cent of anhydrous calcium chloride added at the grinding stage of manufacture.

Cements containing more than 1·5 per cent of anhydrous calcium chloride are not recommended for use in reinforced or prestressed concrete.

This cement is used when very high early strength is required, or for concreting in cold weather. The rate of heat evolution is increased and the setting process is accelerated; the concrete should therefore be placed and compacted within 30 minutes of mixing.

Ultra high early strength cement: is a very finely divided Portland cement with a higher proportion of gypsum than ordinary Portland cement but otherwise complying with BS12. The initial development of strength is much more rapid than that of ordinary or rapid-hardening Portland cements but there is little increase in strength after 28 days. The heat of hydration is greater at very early ages than that of rapid-hardening Portland cements. It is suitable for use in reinforced or prestressed concrete, but the creep of the concrete may be higher than that of concrete made with other Portland cements.

Table 1 Cements: properties

Cement type	BS No	Rate of strength development	Rate of heat evolution	Resistance to sulphates
Main types of Portland cement				
Ordinary	12	medium	medium	low
Rapid-hardening	12	high	high	low
Sulphate-resisting	4027	low–medium	low–medium	high–very high
Other types of Portland cement				
Extra-rapid-hardening	—	high–very high	high–very high	low
Ultra high early strength	—	high–very high	high–very high	low
Low heat	1370	low	low	medium–high
Waterproof and water-repellent	—	Properties similar to those of ordinary Portland cement		
Hydrophobic	—			
White	12			
Coloured	12			
Cements containing blastfurnace slag				
Portland-blastfurnace	146	low–medium	low–medium	low–medium
Low heat Portland-blastfurnace	4246	low	low	medium–high
Supersulphated	4248	medium	low	high–very high
High alumina cement	915	very high	very high	very high
Pozzolanic cement	—	low	low–medium	medium–high

Low heat Portland cement: intended for use in large masses of concrete to reduce the temperature rise in the concrete and the possibility of subsequent cracking. It develops strength more slowly than ordinary Portland cement, particularly at low temperature, but its final strength is not lower. It usually offers better resistance to attack by sulphate waters than ordinary Portland cement. This cement is manufactured only to special order.

Waterproof and water-repellent cements: concrete made with these cements under site conditions is somewhat less permeable to water and to some oils than concrete made with ordinary Portland cement. Some types tend to entrain air during the mixing process and this must be carefully controlled to avoid excess air-entrainment with consequent reduction in strength. Low permeability depends, as always, upon a good dense concrete being made.

Hydrophobic cement: has been developed to prevent partial hydration of cement during storage in unavoidably humid conditions. Substances added during the grinding process form a water-repellent film round each grain of cement. The protective film is rubbed off during mixing and hydration takes place normally. This cement is manufactured only to special order.

White Portland cement: made by selection of the raw materials and by special manufacturing processes and meets the requirements of BS12.

Coloured cements: are basically white or ordinary Portland cements to which between 5 and 10 per cent of pigment has been added, usually at the grinding stage. The pigment, being inert, dilutes the cement and the strength of the concrete will be slightly reduced; if necessary, this can be compensated by increasing the cement content of the mix by about 10 per cent.

Portland-blastfurnace cement: is made by grinding a mixture of granulated blastfurnace slag and ordinary Portland cement clinker or mixing ground granulated blastfurnace slag and Portland cement. It is similar to ordinary Portland cement but its strength development is somewhat slower; it therefore requires longer curing periods, particularly in cold weather. Portland-blastfurnace cement is useful when concreting large masses. It is also slightly more resistant to attack by sulphates than ordinary Portland cement. This cement is normally only available in Scotland.

Low heat Portland-blastfurnace cement: similar to Portland-blastfurnace cement but with a higher

slag content; intended for use in large masses and cement-rich thick sections of concrete to reduce temperature rise and subsequent cracking. It develops strength more slowly than ordinary Portland cement, particularly at low temperature, and is more resistant to sulphate attack than Portland-blastfurnace cement and ordinary Portland cement.

Supersulphated cement: consists of granulated blastfurnace slag, calcium sulphate and a small amount of Portland cement. Its resistance to attack by sulphates over the range of concentrations commonly encountered in groundwaters is similar to that of sulphate-resisting Portland cement. It has been found that good quality concretes prepared from supersulphated cement have an acceptable life in mildly acid conditions. Care in curing, particularly during the first few days, is needed to reduce surface dusting.

High alumina cement: differs in its manufacture and characteristics from Portland cements. Concrete made with it develops very high early strength allowing it to be brought into early use, and this is particularly useful in cold weather. Heat evolution is very rapid and the temperature rise may need to be checked by cooling; if at any time the temperature of the concrete exceeds about 30°C in moist conditions, the concrete will lose a substantial proportion of its strength. This loss of strength is much reduced in mixes of low water/cement ratio (0·5 or less). High alumina cement has high resistance to attack by acids and sulphates; it is widely used in refractory concrete.

Pozzolanic cements: mixtures of a Portland cement and a natural or artificial pozzolanic material, such as pulverised-fuel ash, that combines with lime (eg lime released by the setting of the cement) at ordinary temperatures in the presence of water to produce compounds with cementing properties. They have been little used in this country but more widely on the Continent and in the USA. They have increased resistance to chemical attack but the rate of strength development is reduced; they have a lower rate of heat evolution and can be used to advantage in mass concrete.

The use of different cements

From the above comments it can be seen that if a cement having a special property is required, then other properties of this cement may restrict its use. Heat of hydration, for example, is linked with the rate of strength development; if a high early strength is obtained the user must be aware that heat will be evolved quickly, and this may not always be desirable. When an unfamiliar type of cement is used for the first time, the user should ascertain how it differs from ordinary Portland cement and any special precautions that should be taken in its use. *Neither high alumina cement nor supersulphated cement must be mixed with any other type of cement or with lime,* and all mixers, plant and tools must be thoroughly cleaned before and after using these cements to avoid interaction with other types.

Aggregates

Aggregates make up the major part of the volume of concrete and their properties affect the characteristics of the concrete. They should not react adversely with the cement, nor contain impurities that do so and they should remain reasonably stable when subjected to changes in moisture content. The use of aggregates that have a high drying shrinkage is described in Digest 35. The shape and surface texture of the aggregate particles and the grading of the aggregate, ie the distribution of particle sizes, are important factors influencing the workability and strength of concrete.

It is convenient to classify aggregates as lightweight or dense, according to their bulk density. BS 3797 defines lightweight aggregates as having a density less than 960 kg/m^3 for coarse aggregate, or 1200 kg/m^3 for fine aggregate.

Dense aggregates

Most aggregates fall into this category; the main functional requirement of concrete made with them is to provide strength and durability. Concretes made with these aggregates may also be required to provide fire protection and the amount of protection they afford will depend on the aggregate used, as discussed later. Reference may also be made to Digest 13 and to the following British Standards:

BS 882	Coarse and fine aggregates from natural sources.
BS 1047	Air-cooled blastfurnace slag coarse aggregate for concrete
BS 1201	Aggregates for granolithic concrete floor finishes

The grading of the fine aggregate (material passing a 5 mm sieve) has a considerable influence on the properties of concrete. Grading limits for natural aggregates are specified in BS 882 and the fine aggregate should comply with one of the four specified grading zones. These zones enable a fine aggregate to be classified according to the proportion of material passing a 600 micrometre sieve. Zone 1 is the coarsest material and zone 4 is the finest. Materials complying with any of the four zones are suitable for making concrete but the mix proportions should be adjusted to obtain the best results.

As an aggregate becomes finer, the surface area of its particles increases and more water is needed to produce a concrete having the required workability;

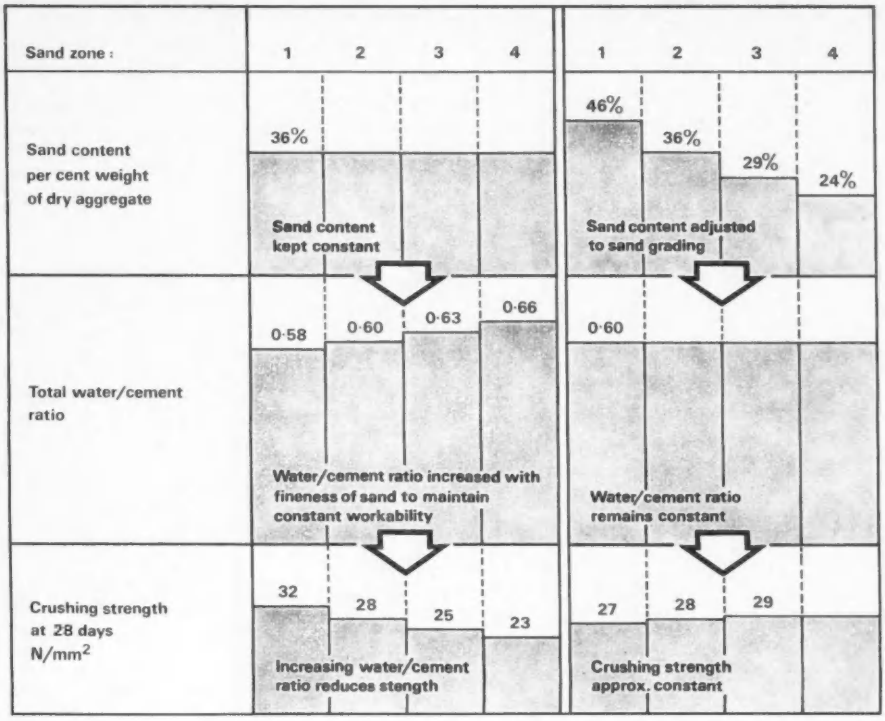

Fig 1 Effect of sand grading on 1 : 6 concrete at constant workability

this results in lower strength concrete. However, concrete with the same strength and workability can be made by the simple process of reducing the content of fine aggregate as this becomes finer, ie moving from zone 1 towards zone 4. Fig 1 shows the effect on a 1 : 6 concrete mix of using sands of different gradings, keeping the workability the same. If the fine aggregate content is not changed, more water will be needed with finer aggregates to produce concrete of the required workability, because of the greater surface area, and lower strength concrete will result.

More natural sands fall into grading zones 3 and 4 than into zones 1 and 2 but crushed rock fines tend to have gradings in zones 1 and 2.

Air-cooled blastfurnace slag coarse aggregate: a by-product of the manufacture of pig iron. Concrete made with slag complying with BS 1047 has properties similar to those of concrete made with natural aggregates complying with BS 882; it also has good fire protection properties.

Crushed brick: should consist of clean crushed bricks, not brick rubble containing mortar and plaster. Bricks usually contain soluble sulphates and if to be used as aggregate the sulphate content should not exceed 1 per cent SO_3. This aggregate has good fire protection properties and can also be used for exposed aggregate surface finishes of a variety of colours.

Lightweight aggregates

The following types of lightweight aggregate are commonly available :

Clinker	BS 1165
Foamed blastfurnace slag	BS 877
Exfoliated vermiculite	BS 3797
Expanded perlite	
Pumice	
Expanded clay, shale or slate	
Sintered pulverised-fuel ash	

Each material has its own characteristics of density, particle shape and surface texture. The grading of the fines generally differs from natural sands being rather coarse but containing a high proportion of very fine particles. A variety of concretes can be made, from lightweight blocks and screeds to dense structural concrete as indicated in Table 2. These aggregates and the properties of concretes made from them are described in Digest 123.

Admixtures

The properties of concrete, both in its plastic and hardened states, can be modified by the use of admixtures. A large number of proprietary preparations are available, some of them containing several substances. Many complex natural products or chemicals may be involved and their selection and use should be based on performance data and trials.

Table 2 Properties of various types of concrete using different aggregates

Aggregate	Typical range of dry density Aggregate kg/m³	Concrete kg/m³	Compressive strength N/mm²	Drying shrinkage per cent	Thermal conductivity at 5% moisture content* W/m °C	Main functional requirement
Clinker	700–1050	1050–1500	2–7	0·04–0·08	0·35–0·65	thermal insulation
Exfoliated vermiculite and expanded perlite	60–250	400–1100	0·5–7	0·20–0·35	0·15–0·39	thermal insulation
Pumice	500–900	650–1450	2–15	0·04–0·08	0·21–0·63	thermal insulation
Foamed slag	300–950	950–1500	2–7	0·03–0·07	0·30–0·65	thermal insulation
Expanded clay, shale or slate and sintered pulverised fuel ash	300–1050	700–1300	2–7	0·03–0·07	0·24–0·50	thermal insulation
Foamed slag	500–950	1700–2100	15–60	0·04–0·10	0·85–1·40	Class 1 fire-resistance
Expanded clay, shale or slate and sintered pulverised fuel ash	300–1050	1350–1800	15–60	0·02–0·12	0·55–0·95	Class 1 fire-resistance
Crushed brick	1100–1350	1700–2150	15–30	—	0·85–1·50	strength and durability
Crushed limestone	1350–1600	2200–2400	20–80	—	1·6 –2·0	strength and durability
Flint gravel or crushed stone	1350–1600	2200–2500	20–80	—	1·6 –2·2	strength and durability

Class 2 fire-resistance

*Calculated from IHVE *Guide*; if available, measured conductivities should be used in preference to these for calculating standard U-values.

Air-entraining admixtures promote the formation of very small air bubbles during mixing and this results in improved durability, particularly frost resistance. The presence of air in the hardened concrete tends to reduce its compressive strength but the workability is improved and thus the water/cement ratio may be reduced which offsets some of the loss of strength. The basis of most air-entraining admixtures is vinsol resin.

Water-reducing or plasticising admixtures, mostly based on calcium lignosulphonate, reduce the attractive forces between cement particles and increase the workability of the wet concrete. At a given water content, the handling and placing qualities of the concrete will be improved and this will assist placing by pump or placing in heavily reinforced sections or constricted formwork. On the other hand, for a given workability the quantity of mixing water can be reduced so that stronger and more durable concrete is obtained. Unless modified by the addition of other, accelerating, agents this type of admixture will retard the rate of setting to some degree and this may sometimes be advantageous. Accelerating admixtures increase the rate of setting and development of early strength; they increase the rate of temperature rise in the setting concrete. They are useful when working in low temperatures or when casting units that are to be handled at an early age. Calcium chloride is the most commonly used accelerating admixture.

The use of admixtures may often require adjustment of the concrete mix, and preliminary site trials may be needed to establish that the admixture provides the required performance without adverse secondary effects. To obtain optimum performance it is essential that the admixture should be uniformly distributed throughout each batch of concrete. Admixtures supplied as water solutions or as water-soluble powders can conveniently be added in the mixing water.

The need for careful selection and control of concrete-making materials, for proper proportioning, batching and mixing, and for appropriate casting and curing techniques is not decreased by the use of an admixture.

Pulverised-fuel ash is a by-product of power station furnaces fired by pulverised coal. It can be used in concrete in two ways: as a constituent of cement, being ground in with the clinker or blended with cement; or it can be added at the mixer with the cement and aggregate.

The action of pulverised-fuel ash in a Portland cement concrete is twofold: it acts as a pozzolana and it modifies the overall grading of the mix. It is commonly used in mass concrete where the effect of replacing a proportion of the cement with pulverised-fuel ash, typically up to 20 per cent, is to reduce the heat generated by hydration of the cement. This leads to a reduction in early strength but by pozzolanic

action this loss can be expected to be recovered within 6 to 12 months. The predominantly spherical shape of the particles improves workability and replacement of some of the fines fraction in a concrete mix by pfa may lead to a better compacted concrete at the same workability, hence to higher strength. By combining these two factors, ie replacing some fine aggregate and some cement in careful mix design, it is possible to achieve the same concrete strength at early ages in mixes containing substantial quantities of pfa as for the corresponding mixes without this addition. BS 3892 gives the minimum requirements for its use in concrete. Reference should, however, be made to the recommendations of the Central Electricity Generating Board for its use in specific applications. Cement/pfa mixes have proved useful in grouting and in concrete pumping and they also improve the resistance of ordinary Portland cement concretes to sulphate attack.

Ground granulated blastfurnace slag can also be used in Portland cement concrete by incorporation at the mixer to replace a proportion of the cement. Strength development at early ages is reduced but this loss is recovered within about two months. By careful mix design and utilisation of the better workability of slag-containing mixes, equivalent strength at early ages can be obtained. Ground granulated slag mixes have proved useful in grouting and concrete pumping and the resistance of ordinary Portland cement concrete to chemical attack may be improved, depending on the amount of slag incorporated.

Concrete properties and choice of materials

Concrete has usually to meet one or more of four functional requirements: strength, durability, fire protection and thermal insulation. Both cements and aggregates are important in relation to strength and durability, but fire protection and thermal insulation depend almost exclusively on the type of aggregate used. Most concrete should be durable under ordinary conditions of exposure but special precautions must be taken when it is exposed to aggressive conditions, such as various forms of chemical attack, frost and fire. In reinforced and prestressed concrete, the concrete must provide effective cover to prevent corrosion of the steel (*see* Digest 59).

There are circumstances when a special combination of types of cement and aggregate is required to produce concrete with special properties. Table 2 shows the characteristics of concrete made with different aggregates, arranged in functional groups. More details about lightweight aggregates are given in Digest 123; not all the lightweight aggregates suitable for thermal insulating concrete are suitable for structural concrete for which purpose different mixes are used.

Strength

Transverse strength There are conditions, as in road slabs, where the transverse or bending strength of concrete is more important than its compressive strength. Concrete made with crushed rock aggregate tends to have a higher transverse strength than concrete of the same compressive strength made with sand and gravel; thus if a concrete is required for its transverse strength, a more economical mix may be possible if crushed rock aggregate is used.

Structural lightweight concrete This type of concrete combines the advantage of a reduction in dead weight by about one-third, with improved thermal insulation and fire resistance, and adequate strength. Mixes richer than those usually associated with lightweight concrete are used and the mix proportions are selected to obtain a workable mix that can be fully compacted into a dense concrete so as to provide cover and bond to the reinforcing steel. The structural applications of lightweight aggregate concrete are discussed in Digest 111.

Durability

Resistance to frost In Britain, concrete is seldom severely damaged by frost but the possibility cannot be entirely neglected unless the concrete is in a sheltered or dry position. To provide frost resistance in situations where concrete can become saturated with water, for example in kerbs, roads and bridges, the free water/cement ratio should be kept as low as possible and should not exceed 0·55.

A high degree of frost-resistance can be obtained by the use of an air-entraining admixture and this is now specified for all concrete subject to the use of salt for de-icing. The air content should be from 4 to 7 per cent, by volume, according to the maximum size of the aggregate used.

The precautions to be taken on a building site during cold weather are given in **Winter building** HMSO (1963).

Resistance to chemical attack A basic requirement for any concrete to withstand chemical attack is that it should have a low water/cement ratio, be thoroughly compacted and properly cured. It may be necessary to use types of cement other than ordinary Portland, such as sulphate-resisting, supersulphated, high alumina or pozzolanic cement. There are many industrial processes in which oils, acids and alkalis can attack concrete, for which special precautions will have to be taken; these generally call for specialist advice.

For concrete in sulphate-bearing soils and groundwaters, *see* Digest 90.

Concrete for fire protection

The behaviour of concrete when subjected to high temperatures, as developed in fires, is largely dependent on the type of aggregate used. Concretes

made with siliceous aggregates have a tendency to spall whereas those containing limestone, blastfurnace slag and lightweight aggregates are virtually unaffected by spalling. Damage by spalling can be reduced by the incorporation of supplementary reinforcement in the concrete cover, but this is not necessary in the case of beams and columns made with limestone aggregate concrete. Limestone aggregate concretes also have a lower thermal conductivity and therefore provide better protection than an equal thickness of other dense concretes.

The accepted classification of aggregates in descending order of fire resistance of the concretes made from them is:

Class 1

(a) Non-spalling, good thermal insulation: Foamed slag and lightweight aggregates complying with BS 3797.

(b) Non-spalling, reduced thermal insulation: Blastfurnace slag, crushed brick and burnt clay products, well-burnt clinker and limestone.

Class 2

Tendency to spall: Siliceous aggregates generally, eg flint gravel, granite and all natural stones other than limestone.

Thermal insulation

To provide good thermal insulation, a concrete must have a low density. For a given density, the thermal insulation will vary depending on the aggregate used and on the amount of free water present (*see* Digest 108). Basically, an insulating concrete is one containing a large amount of air voids and this can be achieved by using lightweight aggregate, aerated concrete, or no-fines (dense or lightweight aggregate) concrete.

No-fines concrete is usually made with aggregate between sizes 20 and 10 mm. It may be used for cast in situ load-bearing walls in single and multi-storey construction. Aerated concrete is described in Digests 16 and 17.

Documents referred to in the text:

BRE digests

16 Aerated concrete—1: Manufacture and properties (revised 1970)

17 Aerated concrete—2: Uses (revised 1971)

35 Shrinkage of natural aggregates in concrete (revised 1971)

59 Protection against corrosion of reinforcing steel in concrete (revised 1970)

90 Concrete in sulphate-bearing soils and groundwaters (revised 1970)

108 Standardised U-values (revised 1972)

111 Lightweight aggregate concretes—3: Structural applications

123 Lightweight aggregate concretes

British Standards

12 Portland cement (ordinary and rapid-hardening): Part 2: 1971 Metric units

146 Portland-blastfurnace cement (1958)

877 Foamed or expanded blastfurnace slag lightweight aggregate for concrete (1967)

882, 1201 Aggregates from natural sources for concrete (including granolithic) (1965)

915 High alumina cement: Part 2: 1972

1047 Air-cooled blastfurnace slag coarse aggregate for concrete (1952)

1165 Clinker aggregate for concrete (1966)

1201 *see* **882**

1370 Low heat Portland cement (1958)

3797 Lightweight aggregates for concrete (1964)

4027 Sulphate-resisting Portland cement: Part 2: 1972

4246 Low heat Portland-blastfurnace cement (1968)

4248 Supersulphated cement (1968)

Department of the Environment *Winter building:* HMSO 1963

Digest 146: Modernising plumbing systems

Amendments

Synopsis; delete the second sentence and substitute:

When undertaking such modernisation, particularly when the extension of an existing system is involved, it is essential to be aware of the problems of corrosion and scaling that may arise.

Page 1; delete para 6 ('Both types of system . . .') and substitute:

If they are supplying only domestic hot water, both direct and indirect systems usually rely on gravity circulation to transfer heat from the boiler to the storage cylinder. The cylinder must then be located at a higher level than the boiler and the pipes must be of adequate size to maintain the flow. Where an indirect system serves a separate space-heating circuit, the water is normally pumped through the circuit to achieve a higher rate of initial heating and to ensure that the rate of water flow through the radiators is sufficient to maintain radiant surface temperatures.

Page 2, para 2; delete the first sentence and substitute:

Calcium bicarbonate, which causes temporary hardness, is decomposed most rapidly where the water is hottest, in the boiler water jacket and near the outlet, often producing heavy calcium carbonate scale at these points.

Page 2, penultimate line; delete the reference to Table 1

Page 3, para 4; delete the first two lines and substitute:

If a flow of water through the expansion pipe into the expansion tank occurs, this can be a further cause of aeration of the water; oxygen can also be . . .

Page 4, Table 1; delete the whole table. This table, although theoretically correct for specific conditions, has proved to be misleading and difficult to interpret. So many explanatory notes would be needed to cover all practical situations in water services that it has been decided to withdraw it.

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